Conf-9108118--34

LBL-30674

Lawrence Berkeley Laboratory

UNIVERSITY OF CALIFORNIA

Accelerator & Fusion Research Division

Presented at the Thirteenth International Free Electron Laser Conference, Santa Fe, New Mexico, August 25–30, 1991, and to be published in the Proceedings

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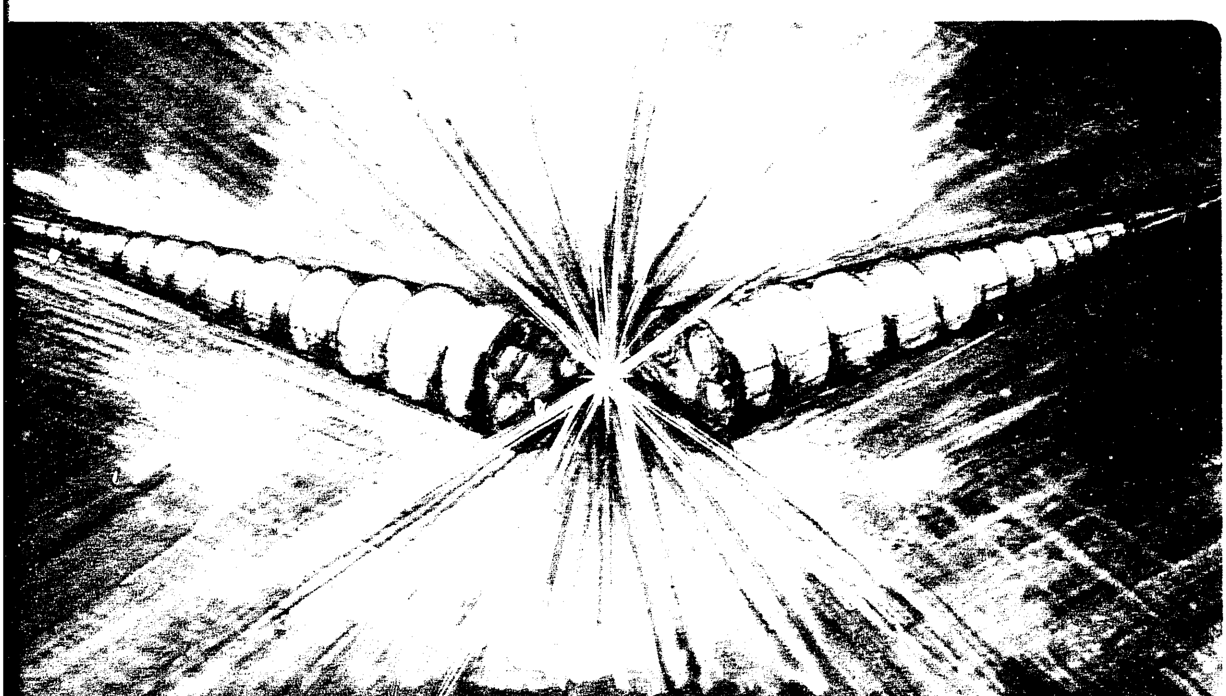
September 1991



Prepared for the U.S. Department of Energy under Contract Number DE-AC03-76SF00098

LBL--30674

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Achromatic and Isochronous Electron Beam Transport for Tunable Free Electron Lasers*

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Abstract

We have continued the study of a suitable electron beam transport line, which is both isochronous and achromatic, for the free electron laser being designed at Lawrence Berkeley Laboratory. A refined version of the beam transport optics is discussed that accommodates two different modes of FEL wavelength tuning. For the fine tuning involving a small change of the electron beam energy, sextupoles are added to cancel the leading nonlinear dispersion. For the main tuning involving the change of the undulator gap, a practical solution of maintaining the beam matching condition is presented. Calculation of the higher order aberrations is facilitated by a newly developed code.

1. Introduction

An infrared free electron laser (IRFEL) is being designed for the Chemical Dynamics Research Laboratory (CDRL) at Lawrence Berkeley Laboratory [1],[2]. Being a user facility for fundamental chemical research, the FEL (henceforth referred to as the CDRL-FEL) must meet a very tight set of performance specifications, especially on various jitters. The beam transport configuration from the accelerator to the FEL must accordingly be carefully designed to satisfy

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these requirement; It must be achromatic [3] to avoid a transverse beam jitter due to an energy jitter, and to avoid exchange of emittances between the longitudinal and the transverse phase space. The transport must also be isochronous to avoid the time of flight jitter due to the energy jitter, and to avoid the lengthening of the bunch.

A preliminary beam transport design was carried out by M. Berz, who worked out a linear achromat with an isochronicity that satisfies the specification [4]. A quadrupole triplet was added at the end of the line, to match the beam for the FEL. In this paper we extend the work to take into account the requirements for FEL wavelength tuning. Two modes of wavelength tuning is envisaged for CDRL-FEL. The main tuning will be accomplished by changing the undulator gap at a fixed electron beam energy. The complete spectral range 3 μm to 50 μm will be covered by running the electron beam at four separate energies and tuning the undulator magnet gap at each electron energy, as shown in Table 1. Thus it is important to require that the matching of the electron optics to the undulator region be maintained while the undulator gap is being changed. In the fine tuning mode, the electron beam energy is changed by a small amount, upto about ± 1 %, at a fixed undulator gap. Thus the transport must be sufficiently dispersion-free so as to allow a small change of the electron beam energy without moving the beam transversely.

In section 2, we study the fine tuning requirement. The nonlinear dispersion turns out to be unacceptable so that sextupoles are added to correct the second order dispersion. The calculation of nonlinear aberrations is facilitated by a new code called COSY- Exterminator [5]. In section 3, we work out a practical solution of maintaining the beam matching during the main tuning mode.

2. Matching at Fixed Undulator Gap and Correction of Nonlinear Effects

The transport line of the previous work consists of a mirror symmetric arrangement of two cells with the following elements [4]: drift, bend, focusing quadrupole, drift and defocusing quadrupole. It is a linear achromat and has an isochronicity within the requirement.

The matching of the beam to the undulator is accomplished by means of a quadrupole triplet at the end of the beam line. The strength of the beam line elements for matched condition, which is discussed in detail in next section, involves linear matrix calculation. This is carried out using the simulation code Tracy [5] and a nonlinear optimizer known as Simplex [6]. The result for matched optics function for a given undulator configuration is shown in Fig.1. The corresponding phase space transformation is shown in Fig.2.

However, the beam transport was found to have a significant nonlinear dispersion as shown in Fig.3. Since it is envisaged to fine tune the FEL wavelength by changing the electron beam energy, it is important that the dispersion be small so that the fine tuning does not result in the transverse beam motion. With the dispersion shown in Fig.4, an energy change of $\pm$ 1% (corresponding to a $\pm$ 2% change in FEL wavelength) would accompany a position change of 0.3 mm and an angle change of 0.4 mrad. Such a movement is unacceptable for the CDRL-FEL. Therefore the nonlinear dispersion is corrected by adding a sextupole next to the bend in each cell to cancel the leading second order contribution. The corrected dispersion is shown in Fig.4. It is now possible to fine tune the electron beam energy upto $\pm$ 1 % without detectable transverse motion.

In calculating the higher order aberrations, we found Cosy-Infinity [7] in the present form to be inadequate for our purpose. Some of the practical problems encountered are as follows:

1. The implementation of the bend is only consistent to first order.
2. Formatted output is not provided.
3. Global arrays cannot be addressed except inside loops using the loop index.

The first item was fixed by using Healy's modular approach [8], which only required some reprogramming at the Cosy-Infinity input file level. The other two items preclude the possibility to store values calculated along a lattice (like Twiss parameters), the printing of tables etc. Since fixing these items would require an improved redefinition of the Foxy language and subsequent modifications at the compiler and interpreter level, we have chosen another approach as follows:

Utilizing the DA-library [9] and the source code of a compiler to a suitable programming language for numerical calculations, the arithmetical expression accepted by the language was generalized to include DA-vectors. By using the Pascal-S compiler/interpreter system [10] and Lie-lib [11] (to be able to do perturbation theory on the map), one of us (J.B.) implemented a powerful and general tool, that has been named Cosy-Exterminator.

Cosy-Exterminator was used to calculate the higher order aberrations as well as calculating the necessary sextupole strength to cancel the second order dispersion. It could also have been used for the matching, but a matrix code in this case is faster. The dispersion before and after correction is shown in Fig. 3 and Fig.4. The final time of flight aberration is given by the following expansion:

$$c\,\Delta\tau\ [\mathrm{m}] = 0.013\,\delta - 0.194\,\delta^2 - 1.040\,\delta^3 + \ldots$$

where $\delta = (p - p_0)/p_0$, p = momentum and p_0 = reference momentum .

3. Beam Line Matching During Undulator Gap Change

For the usual case where the cavity mirrors are placed symmetrically about the undulator, the electron beam waist should be at the center of the undulator. In the horizontal direction, there is no focussing in the undulator. In this case, the value of the beta function at the waist (which corresponds to the Rayleigh range for radiation) should be about half of the length of the undulator, which in our case is 2 m. Thus the condition for the matched beam in the horizontal plane are

$$\alpha_x = 0, \qquad \beta_x = 1\ \mathrm{m},$$

at the center of the undulator. In the vertical plane, we have constant focussing due to the undulator magnetic field with a corresponding effective beta value. The matching conditions in the vertical direction are therefore

$$\alpha_y = 0\ , \quad \beta_y = \frac{\gamma\lambda_u}{\sqrt{2}\,K\,\pi}$$

where K is the deflection parameter, λ_u the period length and γ the relativistic factor.

The previously mentioned matching conditions depend on the electron beam energy and the magnetic field strength K. Thus the transport system has to be retuned whenever the undulator gap or the electron beam energy is varied to scan the FEL wavelength. This involves retuning five quadrupole strengths and one sextupole strength. Using the values presented in Table 1, we find that β_y will be varying between

$$\beta_y = 0.22 - 1.37 \text{ m.}$$

It is thus necessary to compute the strength of the beam line elements as a function of β_y in this range.

Solutions have been calculated for the two cases: $\beta_y = 0.25$ and 1.1 m. Taylor expansions for the parameter dependence have also been calculated to 4th order, using Cosy Exterminator. The interval has been divided into 23 steps with a step size of 0.05 and the Taylor expansions are calculated at each step. Interpolation can then be done within each interval. An example is given in Table 2. In Table 3, the interpolated values are compared with results from a non-linear optimizer or analytical calculations. Note that the quadrupole and sextupole strengths are defined by

$$k = \frac{q}{p_0}\frac{\partial B_y}{\partial x}, \quad k' = \frac{q}{p_0}\frac{\partial^2 B_y}{\partial x^2}$$

where q is the electron charge. A change of energy is therefore easily accounted for by a simple scaling of the current through the multipole magnets by

$$I \rightarrow \quad I\,(1 + \delta)$$

assuming the field to be linear in the current.

We would also like to point out the importance of diagnostics to be able to verify the correct tuning of the transport line. By placing a scintillator at a dispersion free point in the line, it is possible to measure the residual dispersion, which can then be minimized for the real system.

4. Conclusions

We have improved the initial transport system, by adding two sextupoles to cancel the leading second order dispersion. We have also studied the problem of matching the beam to the undulator for different operating conditions. The performance of the system is based on cancellations of aberrations by a symmetrical arrangement of two cells. Misalignment and multipole errors will therefore affect the performance. These effects should therefore also be studied.

Acknowledgments

We would like to thank E. Forest for pointing out Healy's modular approach to the general bend, allowing a consistent implementation to any order. He also participated in the debugging and the checking of the used codes.

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Table 1: Undulator Parameters and Wavelength Coverage

Period length	$\lambda_u = 5$ cm
Number of periods	N = 40
Magnet gap	20.5 mm $\leq$ gap $\leq$ 31.8 mm
Deflection parameters	$2.01 \geq K \geq 0.9$

Wavelength coverage

$E_e = 55.2$ MeV	$6.45\ \mu m \geq \lambda \geq 3\ \mu m$
$E_e = 39.1$ MeV	$12.9\ \mu m \geq \lambda \geq 6\ \mu m$
$E_e = 27.65$ MeV	$25.8\ \mu m \geq \lambda \geq 12\ \mu m$
$E_e = 19.55$ MeV	$53.75\ \mu m \geq \lambda \geq 25\ \mu m$

Table 2: Matching Formulas, Expanded around $\beta_y = 0.25$

$$\Delta qf = 0.0072396\, \Delta\beta_y - 0.0230674\, \Delta\beta_y^2 + 0.0719666\, \Delta\beta_y^3 - 0.2486836\, \Delta\beta_y^4 + \ldots$$

$$\Delta qd = -0.9349138\, \Delta\beta_y + 2.9761665\, \Delta\beta_y^2 - 9.2763185\, \Delta\beta_y^3 + 32.0329285\, \Delta\beta_y^4 + \ldots$$

$$\Delta q1 = -0.0289946\, \Delta\beta_y - 0.0676126\, \Delta\beta_y^2 + 0.2456060\, \Delta\beta_y^3 - 0.9487454\, \Delta\beta_y^4 + \ldots$$

$$\Delta q2 = 1.0027648\, \Delta\beta_y - 0.7585233\, \Delta\beta_y^2 + 1.8353735\, \Delta\beta_y^3 - 4.82572133\, \Delta\beta_y^4 + \ldots$$

$$\Delta q3 = 0.1969058\, \Delta\beta_y - 0.4568777\, \Delta\beta_y^2 + 1.3859026\, \Delta\beta_y^3 - 4.6776913\, \Delta\beta_y^4 + \ldots$$

$$\Delta sf = -99.8477690\, \Delta qf - 0.7476536\, \Delta qd - 9.5841946 \Delta qf\, \Delta qd - 44.6619923\, \Delta qf^2 - 0.0733978\, \Delta qd^2 + \ldots$$

$$\Delta sd = -\Delta sf$$

Table 3: Interpolation from $\beta_y = 0.25$ to 0.30

Multipole Component	Interpolation	Non-linear Optimizer
qf	20.80235	20.80235
qd	-16.11039	-16.11042
q1	26.98922	26.98922
q2	-23.09425	-23.09425
q3	21.90786	21.90787

Multipole Component	Interpolation	Analytical Calculation
sf	422.98484	422.98483
sd	-422.98484	-422.98483

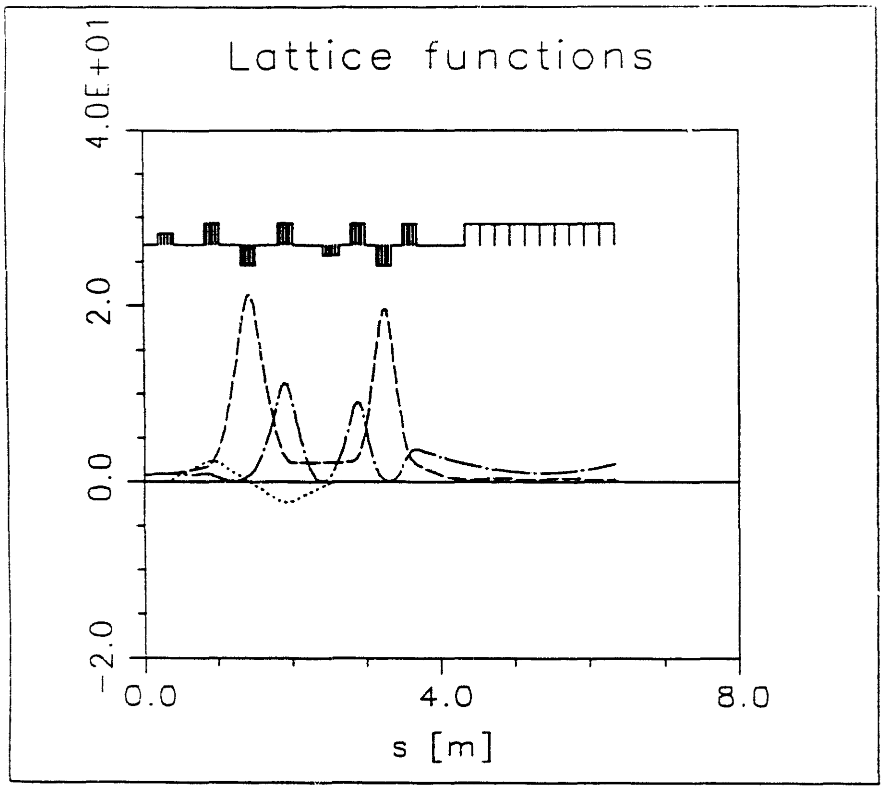

Figure 1: Linear Lattice Functions for $\beta_y = 0.25$.

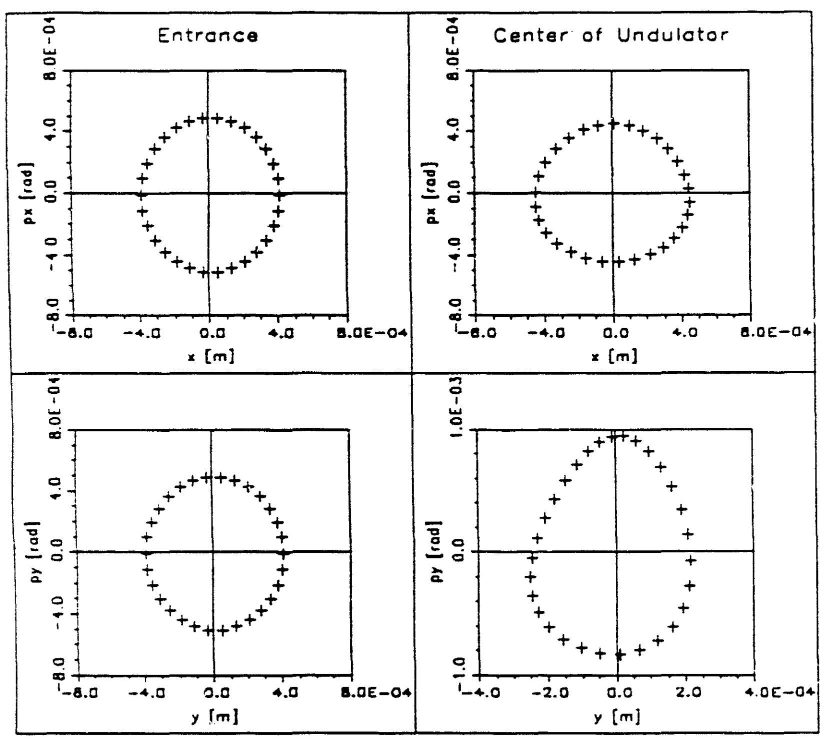

Figure 2: Phase Space for $\beta_y = 0.25$.

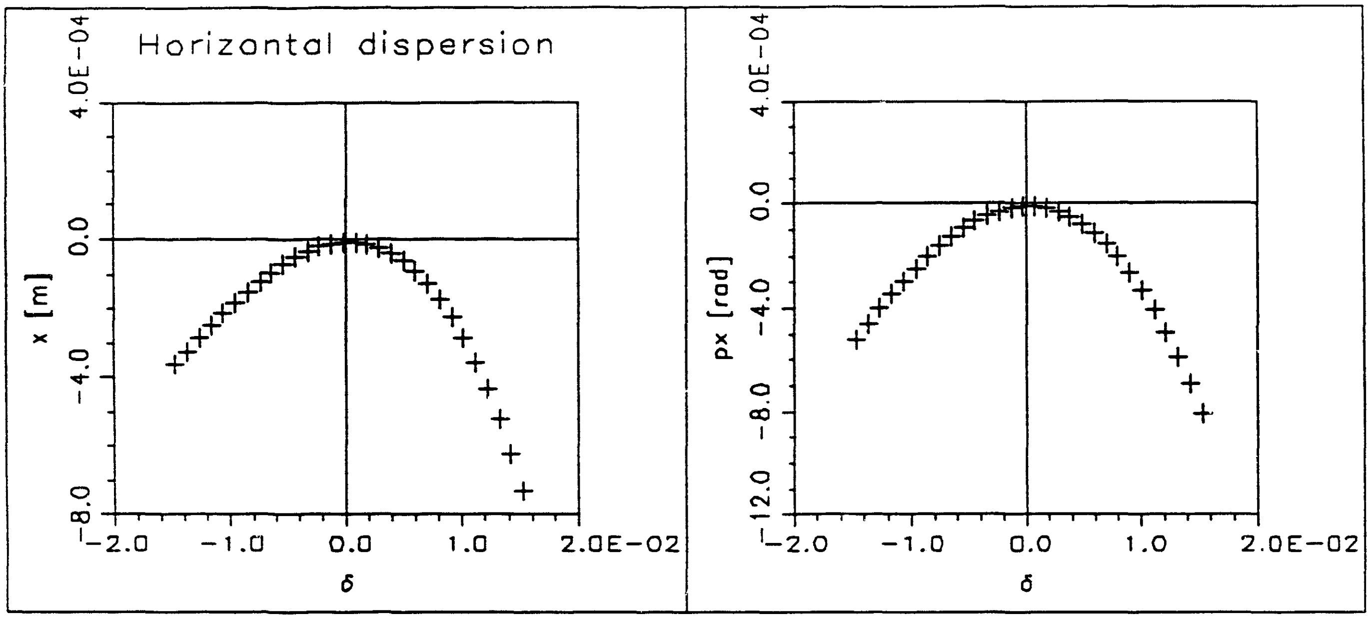

Figure 3: Uncorrected Dispersion.

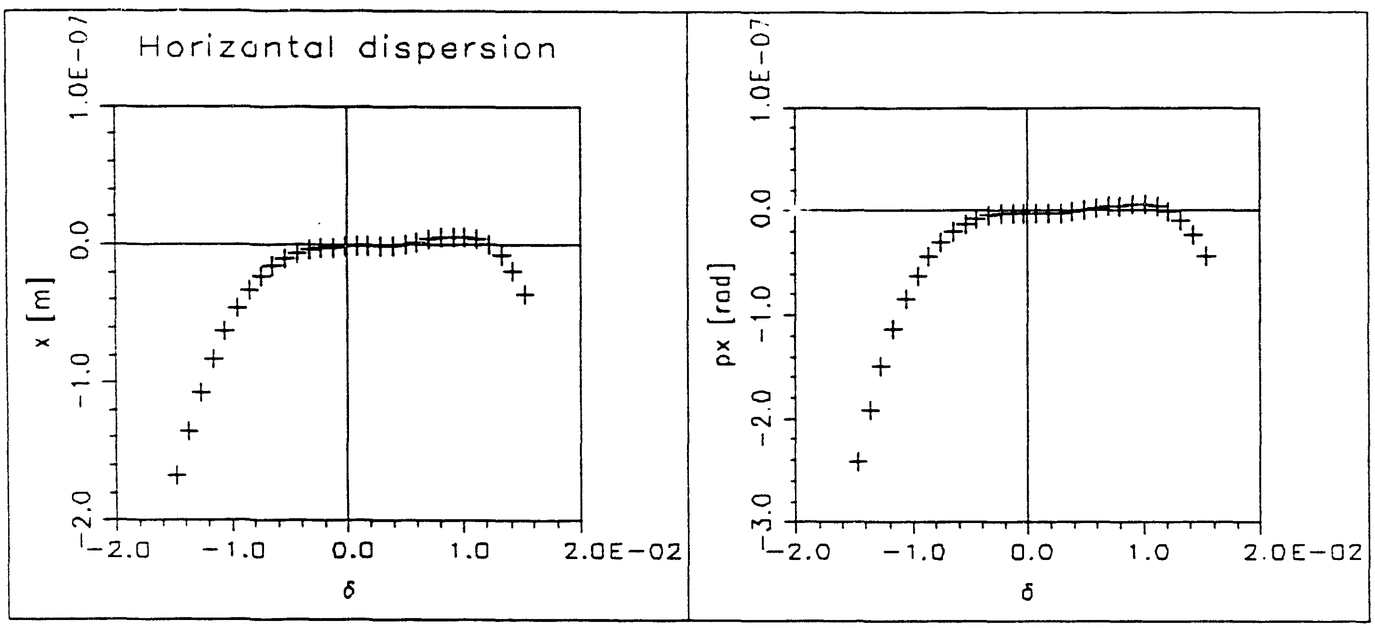

Figure 4: Corrected Dispersion.